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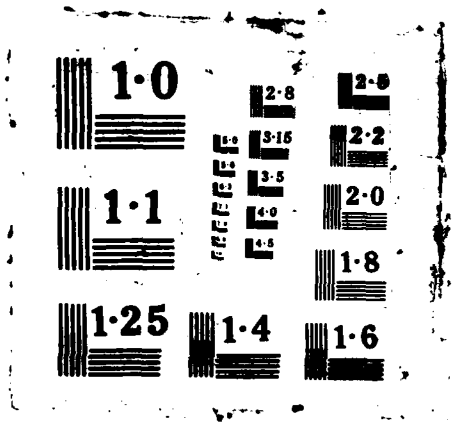
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This report reviews the program of work performed under Grant AFOSR-84-0042 during the period:1 June 1985 - 30 September 1986. The following subjects were treated: examination of material behavior at extreme conditions of temperature and strain rate with respect to a set of elastic-viscoplastic constitutive equations; generalization of those equations to large deformations with particular attention to temperature effects and with applications to cyclic loading and the response of two phase materials; stress waves in composite materials; and the effects of damage development on the response of metals and composites.

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Final Scientific Report

THERMOMECHANICAL EFFECTS IN INELASTIC MATERIALS AND STRUCTURES

by

Sol R. Bodner*
Principal Investigator

Abstract

This report reviews the program of work performed under Grant AFOSR-84-0042 during the period:1 June 1985 - 30 September 1986. The following subjects were treated: examination of material behavior at extreme conditions of temperature and strain rate with respect to a set of elastic-viscoplastic constitutive equations; generalization of those equations to large deformations with particular attention to temperature effects and with applications to cyclic loading and the response of two phase materials; stress waves in composite materials; and the effects of damage development on the response of metals and composites.

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Objectives and Achievements

The overall objective of the research program was to examine the influence of temperature on the inelastic properties of materials and structures. For this purpose, a set of elastic-viscoplastic constitutive equations (those of Bodner-Partom) was taken as the reference representation of material response to thermomechanical loading. These equations have undergone extensive development in the "small strain" format and include basic temperature dependence of inelastic flow through certain material parameters being functions of temperature. In addition, the equations consider thermal recovery of hardening and are potentially capable of accounting for various thermomechanical coupling effects.

Part of the research work performed during the current reporting period, 1 June 85 - 30 Sept. 86, is a continuation of projects described in the previous scientific report for the period 1 Jan. 84 - 31 May 85. A list of scientific papers prepared under the research grant during the previous period, numbering 1-8, is given in this report on pp 8-11. The list of publications for the current period is given on pp 12-17, numbering 9-19 for clarity.

One of the research subjects consisted of examining the predictive capability of the reference constitutive equations under extreme conditions of temperature and strain rate (paper no.9 in the current list of publications). The equations do predict the relatively high values of the flow stress and its rate insensitivity at the very low temperatures. Also, they predict correspondingly high stress levels and temperature insensitivity at very high strain rates. A "built-in" characteristic of these equations is a limiting plastic strain rate in shear. This leads to a convenient and accurate analytical form for representation of inelastic flow up to reasonably high strain rates. The physical basis of this conjecture is discussed in paper no.9.

Generalization of the constitutive equations to large deformations with the inclusion of temperature effects has been carried out independently by Rubin and by Aboudi. An initial development of such a large deformation theory was presented by Rubin in paper no.8 of the earlier list of publications. This formulation was based on a Lagrangian treatment with close attention to thermodynamic restrictions. A slightly revised version of these large deformation constitutive equations appears as part of paper no.10 by Bodner and Rubin in the publication list for the current period. Another aspect of paper no.10 was examination of a modified form of the flow law to account for loss of parallelism between the plastic strain rate and deviatoric stress under nonproportional loading conditions. A possible means of including this effect in the response equations was described.

One of the important exercises of interest for large deformation theories is the combined extension and twist of a long rod which leads to nonlinear couplings known as the "Poynting effect" for elastic materials and the "Swift effect" for plastic media. As a step in treating the general problem, Rubin examined certain theoretical formulations for compressible nonlinear elastic materials in paper no.11 with regard to the "Poynting effect".

A more extensive revision of the large deformation constitutive equations was presented by Rubin in paper no.12 of the current list. Part of the motivation of this work was the intention to obtain particular forms of the constitutive equations for limiting conditions of infinite and zero resistance to plastic flow where the latter could correspond to melting. In this formulation, the analytical form for inelastic flow that exhibits a limiting plastic strain rate is modified to lead to linear viscous behavior at the very high strain rates, while the response at the lower strain rates remains essentially unchanged. The modified equations reduce to that of a general hyperelastic solid for infinite resistance to plastic flow and that of a general Reiner-Rivlin fluid for zero resistance. For the case of "small strains" and with plasticity considered, the limit at high strain rates would be the Maxwell solid and that at melting would correspond to a viscoelastic fluid.

An alternative procedure for generalization of the elastic-viscoplastic constitutive equations was developed by Aboudi in paper no.13 which was primarily directed toward applying the results to two phase composites.

Aboudi's procedure is along more conventional lines and utilizes the Jaumann transformation for the stress rates. In comparison, such a transformation is not required in Rubin's method in which the stress is determined from deformation quantities. Aboudi's formulation can be applied to various special cases such as nonlinearly elastic composites and rate independent elastoplastic work-hardening materials containing a geometrical array of voids. Aboudi shows good agreement between his predicted results and those of other analytical approaches and experimental data for a number of special cases.

As a consequence of Aboudi's extensive research work on elastic-viscoplastic composites, which are intended to be applicable to metal matrix composites, he was requested to write a review article for Solid Mechanics Archives which publishes summary papers on new developments in solid mechanics. This article appears as paper no. 14 in the list of publications. The work performed on thermal effects in metal matrix composites, which was published in a series of papers given in the earlier listing, is summarized in the current review article.

The micromechanics model used by Aboudi in his treatment of thermo-elastic-viscoplastic composites was adopted by him as a basis for analyzing elastic wave propagation in two and three dimensional composites. Two phases are considered each of which is assumed to be generally elastically orthotropic. Paper no. 15 in the list of publications is concerned with harmonic waves while paper no. 16

deals with transient waves in composite materials.

Damage development in stressed metals is particularly important at elevated temperatures due to the formation of voids at grain boundaries and, in metal matrix composites, due to debonding of reinforcement fibers at the interfaces. A study of the consequences of considering continuum damage development on the response properties of metals was carried out in paper no.17 by Bodner and Chan. Both isotropic and directional damage was formulated. Only isotropic damage was considered in exercises that were compared to test data obtained for high temperature creep.

The continuum treatment of damage appears to be reasonable for single phase metals, but a more detailed geometric description of damage appears to be necessary for composites. In paper no.18, Aboudi analyzes the loss of elastic stiffness of certain classes of composites due to the presence of periodic arrays of cracks. A particularly important problem for composites is that of imperfect bonding of the constituents which could have an adverse effect on the response characteristics. This problem is treated by Aboudi in paper no.19 for the case of elastic constituents. The analysis predicts the overall moduli and the coefficients of thermal expansion in the presence of imperfect bonding of the constituents.

Personnel

In addition to the Principal Investigator, Professor S. R. Bodner, the following persons were engaged on the research program:

Professor Jacob Aboudi (Tel Aviv University)

Dr. Miles Rubin (Technion)

Professor Bodner and Dr. Rubin participated in the Jean Mandel Memorial Symposium: "Physical Basis and Modelling of Finite Deformation of Aggregates", Paris, France, 30 Sept.-2 Oct. 1985; paper no.10 was presented at the symposium. Professor Bodner presented paper no.17 at the IUTAM Symposium on Mechanics of Damage and Fatigue, Haifa and Tel Aviv, Israel, 1-4 July 1985; and paper no. 9 at the Conference on Fragmentation, Form and Flow in Fractured Media, Neve Ilan, Israel, 6-9 Jan. 1986. Professor Aboudi gave a lecture on thermo-viscoplasticity of composites at the Annual Technical Meeting of the Society of Engineering Science, State University of New York at Buffalo, 25-27 August 1986. Professor Aboudi is on sabbatical leave for the academic year 1986-87 at the Virginia Polytechnic Institute, Blacksburg, Virginia.

Publications of Research Program

(completed and submitted for publication during previous reporting period: 1 January 84 - 31 May 85)

1. "Review of a Unified Elastic-Viscoplastic Theory", by S. R. Bodner, Interim Scientific Report on Grant AFOSR-84-0042, October 1984, to be published as a chapter in: "Unified Constitutive Equations for Plastic Deformation and Creep of Engineering Alloys", (A. K. Miller, editor), Elsevier Applied Science Pub., Englan(

Abstract - A review is given of a set of constitutive equations for elastic-viscoplastic materials that do not require a yield criterion or loading and unloading conditions. In their present state of development, the equations can provide for certain important characteristics of strain rate dependent inelastic deformation namely: isotropic and directional hardening leading to cyclic stress-strain relations with cyclic hardening or softening, additional hardening due to nonproportional loading, thermal recovery of both isotropic and directional hardening, temperature and pressure dependence, and isotropic and directional damage development. The equations have been used to model a number of metals over a wide range of temperatures and strain rates and examples are presented. Applications of the equations to various engineering problems are described.

2. "The Effective Thermomechanical Behavior of Inelastic Fiber-Reinforced Materials", by J. Aboudi, International Journal of Engineering Science, Vol.23, 1985, pp 773-787.

Abstract - A continuum theory is presented for the prediction of the average behavior of unidirectional fiber-reinforced materials in which both constituents are thermoelastic in the linear region and thermo-inelastic in the nonlinear region. The resulting effective constitutive equations are given by a set of temperature dependent incremental relations from which the response of the composite to a given mechanical and thermal loading can be determined. The derived theory is applied to investigate the overall behavior of unidirectional graphite fibers reinforcing an aluminum alloy matrix under various types of applied stresses and temperature changes. In particular, the effect of residual stresses developed when the composite is cooled is investigated.

3. "Inelastic Behavior of Metal-Matrix Composites at Elevated Temperature", by J. Aboudi, International Journal of Plasticity, Vol.1, 1985, pp 359-372.

Abstract - A set of constitutive relations are given for the prediction of the overall behavior of fiber-reinforced materials, in which both matrix and fiber constituents are thermoelastic-thermoviscoplastic materials. The temperature-dependent response of the composite to a given loading is determined from the set of equations by an incremental procedure in time. The theory is applied to investigate the overall response of unidirectional graphite thermoelastic fibers reinforcing an elastic-thermoviscoplastic aluminum matrix to thermal and mechanical loadings. The residual micro-stresses and microstrains which develop in the composite when it is cooled from its curing temperature are investigated. The effect of this residual field on the overall behavior of the composite when it is subjected to various types of mechanical cyclic loadings is studied.

4. "Constitutive Relations for the Thermomechanical Behavior of Fiber-Reinforced Inelastic Laminates", by J. Aboudi, Journal of Composite Structures, Vol.4, 1985, pp 315-334.

Abstract - The thermomechanical behavior of laminated composites in which every lamina is unidirectional fiber-reinforced thermo-inelastic material is determined by a micromechanical analysis followed by a macromechanics one. In the micromechanics analysis, effective constitutive relations are derived for unidirectional fibrous materials in which the matrix and fiber phases are thermoelastic in the linear region and thermo-inelastic in the nonlinear region. The derivation is based solely on the material properties of fibers and matrix and amount of reinforcement. By a macromechanics analysis, the gross behavior of the laminated composite in stretching and bending deformation is determined. Applications are given for the deformation field developed in cooling and reheating of graphite/aluminum laminated plates.

5. "Effective Thermoelastic Constants of Short-Fiber Composites", by J. Aboudi, Fibre Science and Technology, Vol.20, 1984, pp 211-225.

Abstract - A unified method of analysis for the determination of the effective thermal expansion coefficients, specific heats, and thermal conductivities of unidirectional short-fiber composites is given. The overall thermal constants of long-fiber and particulate composites are obtained as special cases. In addition, the method provides the effective thermal coefficients of isotropic and quasi-isotropic composites with randomly oriented short fibers.

6. "Minimechanics of Tri-Orthogonally Fibre-Reinforced Composites: Overall Elastic and Thermal Properties", by J. Aboudi, Fibre Science and Technology, Vol.21, 1984, pp 277-293.

Abstract - A method is given for the prediction of the effective elastic moduli and coefficients of thermal expansion of composite materials reinforced in three orthogonal directions. The proposed approacn is based on the minimechanics analysis of a repeated representative cell of the three-dimensionally oriented fiber composite. Illustrations are given for a carbon/carbon composite.

7. "Elastoplasticity Theory for Porous Materials", by J. Aboudi, Mechanics of Materials, Vol.3, 1984, pp 81-94.

Abstract - A continuum theory is derived for the modeling of elastoplastic work-hardening porous materials. The theory provides a set of constitutive relations which, using the properties of the inealstic matrix, determines by an incremental procedure the overall response of the porous solid to various types of loading. In the elastic region, effective elastic moduli of the porous material are obtained. Comparison with theoretical and experimental results are given.

8. "An Elastic-Viscoplastic Model for Large Deformation", by M. B. Rubin, International Journal of Engineering Science, Vol.24, 1986, pp 1083-1095.

Abstract - In this paper we have shown that the theory of an elastic-viscoplastic work hardening material proposed by Bodner and Partom (1975) and Bodner (1984) for small deformations may be generalized for large deformations by reformulating the equations using Lagrangian quantities. Restrictions on the general constitutive equations were obtained using the thermodynamic procedures proposed by Green and Naghdi (1977, 1978a). In this formulation, the stress is determined directly from deformation quantities and, in particular, is not calculated using a hypo-elastic type equation for a stress rate. Also, since Lagrangian quantities are used, there is no need to introduce special rates like the Jaumann rate in the evolution equations. Specific constitutive equations were proposed for a material exhibiting isotropic-elastic response in its reference configuration, strain-rate and temperature dependent plastic flow with isotropic and directional hardening, and thermal recovery of hardening. These specific equations use only the material constants obtained from the corresponding small deformation theory. Examples of simple tension and simple shear show that these equations predict physically plausible material response for large deformations.

Publications of Research Program

(completed and submitted for publication during current reporting period: 1 June 85 - 30 September 86)

9. "Constitutive Equations for Metals at High Strain Rates", by S. R. Bodner, Proceedings, Conference on Fragmentation, Form and Flow in Fractured Media (R. Englman and Z. Jaeger, editors), Annals of the Israel Physical Society, Adam Hilger Ltd., Pub., Bristol, England, 1986, pp 595-606.

Abstract - Problems of high velocity impact, explosive loading, and fragmentation are characterized by high strain rates and temperatures. A set of constitutive equations for elastic-viscoplastic material response is described which appears to be applicable to metals and some non-metals under those conditions. These equations include a limiting value of plastic strain rate in shear and lead to a significant increase in the flow stress at the higher strain rates.

10. "A Unified Elastic-Viscoplastic Theory with Large Deformations", by S. R. Bodner and M. B. Rubin to be published as a chapter in: "Large Deformations of Solids: Physical Basis and Mathematical Modelling" (J. Gittus and J. Zarka, editors), Elsevier Applied Science Pub., England, in press.

Abstract - A review is presented of a set of elastic-viscoplastic constitutive equations that incorporate isotropic and directional hardening and additional hardening due to nonproportional loading. These equations employ the isotropic form of the flow law in the presence of directional hardening and a physical argument is given to justify this use. An alternative form of the flow law is also suggested that could account for deviations of the directions of stress and plastic strain rate. Generalization of the theory to large deformations has been carried out using Lagrangian quantities and thermodynamic restrictions. Examples of simple tension and simple shear show that the large strain theory produces physically plausible results.

11. "Pure Measures of Distortional Deformation in Isotropic Compressible Nonlinear Elastic Materials", by M. B. Rubin, Journal of Elasticity, in press.

Abstract - Two scalar invariants are introduced as pure measures of distortional deformation in isotropic compressible nonlinear elastic materials. It is shown that the constitutive equations for pressure and deviatoric Cauchy stress may be conveniently represented when the strain energy function is expressed in terms of these invariants and the usual pure measure of dilatation. Finally, specific constitutive equations are proposed and it is shown that the magnitude of the Poynting effect is controlled by a quantity which characterizes coupling between dilatational and distortional deformations.

12. "An Elastic-Viscoplastic Model Exhibiting Continuity of Solid and Fluid States", by M. B. Rubin, International Journal of Engineering Science, in press.

Abstract - In this paper specific unified constitutive equations for an elastic-viscoplastic material are developed which in the limit of infinite resistance to plastic flow, become those of a general hyperelastic isotropic material; and in the limit of zero resistance to plastic flow, become those of a general Reiner-Rivlin fluid. The constitutive equations satisfy the restrictions imposed by continuum thermodynamics and are hyperelastic in the sense that the symmetric Piola-Kirchhoff stress is related to a derivative of the Helmholtz free energy. In this formulation the Helmholtz free energy depends on five scalar invariants: two new scalars which are pure measures of "elastic" distortional deformation, a measure of total dilatation, a measure of plastic dilatation, and temperature. Specifically, the stress is not characterized by a hypoelastic equation so no special rates of stress need be considered. Both isotropic and directional hardening are included. Finally, examples of simple shear are considered to examine the solid-like and fluid-like response to large deformations including cycles of loading, unloading and reloading.

13. "Overall Finite Deformation of Elastic and Elasto-Plastic Composites", by J. Aboudi, Mechanics of Materials, Vol.5, 1986, pp 73-86.

Abstract - A set of constitutive relations are derived for the prediction of the average finite deformation of composite materials whose constituents are either nonlinearly elastic or nonlinearly elastoplastic materials. The average response of the composite to a given type of loading is solely determined from the known mechanical properties of the phases and their relative volumes. Particulate composites including porous materials, as well as short-fiber and periodically bilaminated composites, are obtained by a proper selection of some geometrical parameters. Comparison with other approaches are made.

14. "Elastoplasticity Theory for Composite Materials", by J. Aboudi, Solid Mechanics Archives, Vol.11, 1986, pp 141-183.

Abstract - In this paper an analytical approach is presented for the modeling of elastoplastic composite materials and the derivation of their overall behavior under various types of loading. The method involves a micromechanics analysis of the inelastic phases, which provides the requested average information from their elastic, inelastic and thermal properties. Rate-dependent (elastic-viscoplastic) as well as rate-independent constituents can be considered by the present method. When the inelastic effects of the constituents are disregarded, the effective elastic moduli and coefficients of thermal expansion of the composite are obtained.

15. "Harmonic Waves in Composite Materials", by J. Aboudi, Wave Motion , Vol.8, 1986, pp 289-303.

Abstract - A continuum model for elastic periodic composites with fibers of finite dimensions is formulated. The proposed theory provides the dispersion relations for harmonic waves in the three-dimensional composite. Dispersion relations of propagating waves normal to the fibers in long-fiber composites, and normal to the layering in periodically bilaminated composites are obtained as special cases. The formulation is given for composites with elastic anisotropic constituents. The predicted acoustical dispersion curves are checked with the exact elasticity solution for laminated composite, and with solutions based on variational principles for fibrous composites. The effect of the strong anisotropy of the fibers in a graphite/epoxy composite is illustrated.

16. "Transient Waves in Composite Materials", by J. Aboudi, Wave Motion, in press.

Abstract - A continuum theory for transient wave propagation in three-dimensional composite materials is given. The derived model provides a set of governing equations for the prediction of dynamic response of elastic composites to impulsive loadings. Pulse propagation normal to the direction of layering in periodically bilaminated media, and normal to the fiber direction in unidirectional long-fiber composites are obtained as special cases. The dynamic response of the composite is determined solely from the material properties of the constituents (assumed in general to be orthotropic) and their geometrical dimensions. The predicted propagating transient waves are checked with exact solutions for impacted laminated composites, and with measured data for a fiber-reinforced material. Applications are given for pulse propagation in particulate composites and in tri-orthogonally fiber-reinforced materials.

17. "Modelling of Continuum Damage for Application in Elastic-Viscoplastic Constitutive Equations", by S. R. Bodner and K. S. Chan, Engineering Fracture Mechanics, in press.

Abstract - A procedure is described for including isotropic and directional damage as load-history-dependent softening variables in a set of elastic-viscoplastic constitutive equations. The evolution equation proposed for isotropic damage integrates to an exponential form for the case of constant stress. Directional damage is represented as a second-order symmetric tensor with a scalar effective value used in the constitutive equations. A method is proposed for treating directional damage in the case of non-proportional loading histories. Comparisons are given of uniaxial creep test results for an alloy at high temperatures with calculations based on the constitutive equations with the inclusion of isotropic damage.

18. "Stiffness Reduction of Cracked Solids", by J. Aboudi, Engineering Fracture Mechanics, in press.

Abstract - A method for the determination of the effective moduli of elastic solids containing a doubly periodic rectangular array of cracks is given. The derivation is based on the analysis of a unit cell in which the displacement vector is expanded to a second order in the distances from centerlines. The equilibrium equations in conjunction with the continuity conditions for the displacements and tractions, give a system of equations for the elastic field variables. The determination of the elastic internal energy provides the requested effective moduli of the cracked body. The method is applied to predict the loss of stiffness of cracked isotropic solids and unidirectional composites, as well as cracked cross-ply laminates.

19. "Damage in Composites: Modeling of Imperfect Bonding", by J. Aboudi, Composite Science and Technology, in press.

Abstract - A model is presented in which the effect of damage due to imperfect bonding between the constituents of composite materials is incorporated. The interface decohesion is described by two parameters which completely determine the degree of adhesion at the interfaces in the normal and tangential directions. Perfect bonding, perfect lubrication and complete debonding are obtained as special cases. The proposed model predicts the overall moduli and coefficients of thermal expansion of composites in the presence of imperfect bonding.

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